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FLIGHT AND TEST-STAND INVESTIGATION OF HIGH-PERFORMANCE FUELS

IN DOUBLE-ROW RADIAL AIR-COOLED ENGINES

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WITH ENGINE COOLING LIMITS IN FLIGHT

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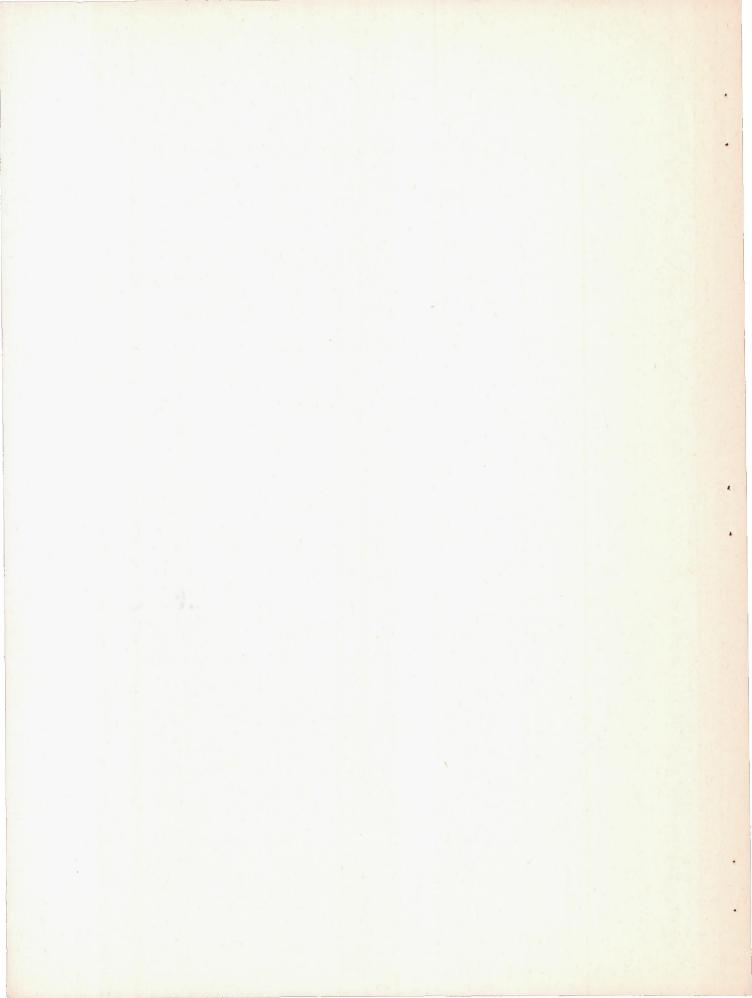
Aircraft Engine Research Laboratory To be returned to Cleveland, Ohio

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

MEMORANDUM REPORT

for the

Army Air Forces, Air Technical Service Command

FLIGHT AND TEST-STAND INVESTIGATION OF HIGH-PERFORMANCE FUELS

IN DOUBLE-ROW RADIAL AIR-COOLED ENGINES

II - FLIGHT KNOCK DATA AND COMPARISON OF FUEL KNOCK LIMITS

WITH ENGINE COOLING LIMITS IN FLIGHT

By H. Jack White, Calvin C. Blackman, and Milton Werner

SUMMARY

A comparison has been made in flight of the anithmock characteristics of triptane with a temperature-sensitive blending agent (xylidines) and of the fuel knock limits with engine cooling limits. The knock limits of three fuels — 28-R, 80 percent 28-R plus 20 percent triptane (leaded to 4.5 ml TEL/gal), and 97 percent 28-R plus 3 percent xylidines (leaded to 6.0 ml TEL/gal) — were investigated with a 14-cylinder double-row radial air-cooled engine installed in a four-engine airplane. The investigation was conducted at an engine speed of 1800 rpm in high blower ratio with two carburetor-air temperatures and at 2230 rpm in high and low blower ratios with one carburetor-air temperature.

The following brief survey is presented of the knock-limited performance characteristics of the two fuel blends relative to 28-R. Because the investigation was conducted with approximately constant cooling conditions, engine-temperature levels were higher with the higher-performance blends.

RATIOS OF KNOCK-LIMITED BRAKE HORSEPOWER OF TEST FUELS

RELATIVE TO 28-R

Conditions	Engine speed, 1800 rpm; carburetor-air temperature, 86° F; high blower ratio	2230 rpm; 2230 carburetor-air carburetor-air temperature, temp 100° F; high 100°		2230 rps carbure tempera 100° F;	ine speed,) rym; puretor-air perature,) F; low wer ratio		
		Fuel-ai	r ratio	· ·			
	0.065	0.065	0.090	0.065	0.090		
80 percent 28-R + 20 percent triptane leaded to 4.5 ml TEL/gal	1.16	1.28	1.19	1.19	1.15		
97 percent 28-R + 3 percent xylidines leaded to 6.0 ml TEL/gal		1.12	1.22	1.30	1.19		

These results for the triptane blend show reasonably good agreement with small-scale single-cylinder test results.

Estimates were made of temperature-limited engine performance at several typical flight and engine conditions. Based on the relations between temperature-limited and knock-limited performance, it appears that, for continuous operation at or near knock-limited power levels with 28-R or with the higher-performance blends, temperatures recommended by the manufacturer for both cylinder heads and bosses will be exceeded.

INTRODUCTION

A general investigation to evaluate triptane and other highperformance fuels as antiknock components of aviation fuels is being
conducted at the NACA Cleveland laboratory at the request of the Army
Air Forces, Air Technical Service Command. Small-scale, singlecylinder knock tests of such fuels are reported in references 1 to 4;
knock-limited performance tests of triptane and five other fuels in a
full-scale air-cooled cylinder are described in reference 5; air-cooled
and liquid-cooled single-cylinder knock tests of a series of fuels

having performance numbers of approximately 150 have been investigated. Knock data from a test-stand investigation have been released in preliminary form; that investigation made use of the test engine and consisted in knock tests of 28-R and 91/96 fuels. The results from flight knock tests with the double-row radial air-cooled engine installed in a four-engine airplane are presented herein. Inasmuch as the engine to be used for additional flight testing of the subject fuel components is a new model, flight tests with the original engine have been terminated.

All the knock data obtained with a double-row radial air-cooled engine in flight for 28-R fuel, a blend of 80 percent 28-R and 20 percent triptane (leaded to 4.5 ml TEL/gal), and a blend of 97 percent 28-R and 3 percent xylidines (leaded to 6.0 ml TEL/gal) are compiled and discussed herein. These fuels will hereinafter be designated 28-R, triptane blend, and xylidine blend. The xylidine blend was chosen because it represents a temperature-sensitive fuel that bridges the gap in performance numbers between the lean rating of 28-R and the rich rating of the triptane blend. The knock ratings of the test fuels, obtained at the Cleveland laboratory, are as follows:

Fuel	Army-Navy perf F-3 rating (lean)	F-4 rating
28-R	100	130
Triptane blend	109	147
Xylidine blend	100	150

All knock-limited performance data reported herein are plotted against fuel-air ratio.

In order to obtain a true picture of the practicability of using a high-performance fuel blend in a given engine and airplane, consideration must be taken of the cooling characteristics of the engine installation as well as of the knock-limited performance the test fuel affords. It is necessary to determine, for a particular engine installation under consideration, whether the utilization of the improved antiknock characteristics of a high-performance fuel blend will result in operation with engine temperatures in excess of the manufacturer's specified values. For this reason the cooling characteristics of the engine were investigated (reference 6) and, from a comparison of the temperature-limited performance with the

knock-limited performance, the feasibility of using high-performance fuels in this engine is discussed herein.

EQUIPMENT AND INSTRUMENTATION

In general, obtaining knock data of the mixture-response type involves making the following measurements, which are of primary interest in determining fuel-knock ratings: engine manifold pressure, brake horsepower, fuel flow, air flow, and inlet-charge temperature. Measurements of various cylinder temperatures must be made to supplement these data inasmuch as fuel-knock characteristics are affected to a certain extent by engine temperature levels. In the performance of tests of this type, the determination of the intensity and the distribution of knock among the cylinders is necessary.

The 14-cylinder double-row radial air-cooled (R-1830-900) engine on which these investigations were made was mounted in the left inboard nacelle of a B-24D airplane. This airplane is shown in figure 1. The equipment and instrumentation of the test engine were the same as described in part in reference 6. The engine is provided with a twospeed mechanical supercharger having a low blower ratio of 7.15:1 and a high blower ratio of 8.47:1. Additional boost was supplied by a turbosupercharger, which is standard for all engines in this airplane. The turbosupercharger was regulated by a direct, manual waste-gate control instead of the semiautomatic boost regulator ordinarily used. A hydraulic torquemeter was used for the measurement of engine power. The torquemeter required modification in order to permit measuring the high powers encountered during the tests. This modification consisted in the substitution of a high-capacity oil-boost pump, mounted at one of the engine accessory drives, in place of the conventional boost pump that is built into the torquemeter.

Fuel knock was detected by means of magnetostriction-type pickups inserted into the combustion chambers of all cylinders. This
installation, with and without the knock pickup, is shown in figure 2.
Fuel knock and other combustion phenomena, as indicated by the knock
pickups, were observed on three oscilloscopes that operated simultaneously through a selector switch. By means of the selector switch,
which could be operated either manually or by a motor, and a fivepoint contactor mounted on the engine, it was possible to survey the
entire engine for either knock or preignition in only five moves of
the selector switch; furthermore, all combustion diagrams normally
appeared at the center of the various oscilloscope screens. This system provided for a rapid inspection of the engine combustion characteristics and enabled a close check to be made for preignition.

Induction-system temperatures were measured in two general regions: at the carburetor upper face and in the 14 intake pipes. Carburetor-air temperatures were measured both by a resistance-bulb unit in the carburetor-inlet elbow and by a thermocouple on the carburetor-inlet screen having the iron junction over one venturi and the constantan junction over the other venturi. The resistance-bulb temperature was used for setting engine conditions when the knock tests were being run because this thermometer closely simulated the standard airplane thermometer installation. All air-flow calculations, however, were based on measurements from the screen thermocouple because the air-box calibration of the carburetor was based on this temperature. Temperatures indicated by bare thermocouples mounted in all intake pipes were recorded as mixture temperatures.

These thermocouples were located approximately $8\frac{1}{2}$ inches downstream

from the supercharger outer case and were centered with respect to

a transverse section through the pipe.

Cylinder-head temperatures were measured by four thermocouples on the cylinder head: one at the front-spark-plug boss, two at the rear-spark-plug boss, and one at the rear-spark-plug gasket. Only two of these temperatures are presented in this report: the rear-spark-plug-gasket temperature, which was measured by a thermocouple attached to a tab on the spark-plug gasket, and the rear-spark-plug-boss temperature, which was measured by a thermocouple embedded 3/8 inch in the head metal at the position shown in figures 3 and 4. The boss thermocouple is designated T38 in figure 3 and the rear-spark-plug-gasket thermocouple is designated T12. The rear-spark-plug-gasket thermocouple corresponds to the installation upon which the manufacturer's operating temperature limits are based, and the embedded rear-spark-plug-boss thermocouple conforms to current NACA practice. (The correlation of cooling characteristics in reference 6 was based on temperatures measured by the embedded thermocouple T38.)

Rear middle-barrel temperatures were indicated by thermocouples spot-welded to the rear outer surface of the cylinder between the sixth and seventh barrel fins, counting from the top fin. The position for this thermocouple (T6) is shown in figure 3.

Cooling-air pressure tubes were also installed to correspond as nearly as possible to the latest NACA practice. (See fig. 5.) A sufficient number of pressure tubes and thermocouples was so installed that a complete cooling correlation of the engine could be made.

Mixture-strength data were determined by two methods: by independent measurements of fuel flow and air flow and by Orsat analysis of the oxidized exhaust gas. Air flow was calculated from an air-box calibration of the PD-12F2-16 carburetor supplemented by a correction curve that was determined by ground air-flow tests with the carburetor installed on the airplane. Fuel flows were simultaneously measured by a rotameter, a deflecting vane-type flowmeter, and a thermal flowmeter developed at the NACA. In most cases fuel-flow data from the deflectingvane-type flowneter were used in calculating the fuel-air ratio. Orsat exhaust-gas analyses were made in flight. Because gas samples were passed through an oxidizing furnace installed in the exhaust stack, it was necessary only to determine the carbon-dioxide content of the oxidized sample. Three samples were taken and analyzed for each knock point. In general, a good check was obtained between fuel-air ratios calculated from fuel-flow and air-flow measurements and exhaustgas analyses. In the presentation of the knock data, calculated fuelair ratios were used wherever possible; however, in a few cases when the carburetor-pressure readings were inaccurate owing to leaking gage lines, the fuel-air ratios were obtained from the Orsat analyses.

Obtaining lean-mixture data was greatly facilitated by the use of a special mixture-control plate in the carburetor. This adaptation, currently being produced by the carburetor manufacturer, provides for a continuous reduction in fuel flow throughout the customary 80° angular travel of the mixture-control arm instead of the abrupt steps (full-rich, automatic-rich, automatic-lean, and idle cut-off) that a standard mixture-control plate affords.

PROCEDURE AND CONDITIONS

Procedure. - In general, knock data were obtained by varying the mixture strength from the value obtained at the full-rich carburetor setting to a minimum value that was usually determined by rough engine operation. Carburetor-air temperature was maintained constant for a group of curves at similar conditions by adjusting the intercooler-shutter setting and, in some cases, by bucking the turbosupercharger output with the engine throttle. This control was necessary because of the wide variation in boost requirement (and consequent turbosupercharger output) for the different fuels. When the knock runs were made at an engine speed of 1800 rpm, it was impossible to maintain a constant carburetor-air temperature over the entire range of boost; that is, from the minimum knock limit of 28-R to the maximum (rich) knock limit of the triptane blend. Consequently, the procedure adopted for the tests at 1800 rpm was to obtain as much of the data as the control of carburetor-air temperature permitted.

The first step in taking knock data was to set the desired knock intensity at a given fuel-air ratio. This knock intensity was that at which four to six cylinders showed occasional or light knock. A subsequent 2-minute period was allowed for engine-temperature stabilization before the 15-second interval during which the actual data were taken. This interval for temperature stabilization was found by a preliminary investigation to be more than sufficient.

The procedure for cooling the engine during the knock tests was to maintain an approximately constant indicated airspeed and cowlflap setting. This procedure, affording an approximately constant cooling-air pressure drop across the engine for all the knock curves, obviated setting a constant head temperature for each knock point and permitted the tests to be run faster. Although engine temperatures varied with fuel-air ratio and power level when this procedure was followed, it was felt that any benefits that might have been gained by maintaining a constant head temperature for each knock point were greatly outweighed by the advantage of obtaining a greater amount of data. By the maintenance of approximately constant cooling-air pressure drop for all runs, the triptane and xylidine blends were tested at higher engine temperatures than 28-R. This procedure, consequently, may have penalized these two blends somewhat in relation to 28-R because, as the data will show, the knock limits of these two fuels were in all cases higher than that of 28-R.

Test conditions. - The following table lists the engine operating conditions at which the various fuels were tested:

Fuel Engine speed (rpm)		Carburetor- air temper- ature (°F)	Blower	
Triptane blend 28-R	1800	61 and 86	High	
Xylidine blend Triptane blend 28-R	2230	100	High and low	

Specific engine conditions pertaining to the various groups of knock curves are listed in the respective figures. In addition, numbers of the flights from which the various knock curves were obtained are given. Table I lists pertinent flight conditions and recorded free-air temperatures according to flight number.

For all flights, a pressure altitude of approximately 7000 feet and an indicated airspeed of approximately 200 miles per hour were maintained. All knock tests were run with full-open (approximately 200 open) cowl flaps on the test engine. The variation in free-air temperature was, of course, due to atmospheric conditions and could not be avoided. A standard spark setting of 250 B.T.C. on both plugs was used for all tests.

RESULTS AND DISCUSSION

Knock-Limited Performance

Presentation of data. - Results of the flight knock tests are plotted in figures 6 to 9; the (a) sheet of each figure shows the significant engine-performance variables, including average mixture temperature, and the (b) sheet shows the engine temperatures. Each of these figures presents knock-limited curves for the different fuels at one set of engine conditions: engine speed, blower ratio, and carburetor-air temperature. The percentage increase in knock-limited performance of the test fuels over that of 28-R is shown in figures 7(a), 8(a), and 9(a) at various fuel-air ratios.

Discrepancies in data. - Of the two sets of data for the triptane blend shown in figure 9(a), the tests made in flight 21 (approximately the same conditions as in flight 16) show an appreciably higher knock-limited performance at fuel-air ratios lower than 0.08 than do the data from flight 16. The only difference between conditions for these runs was that an unusually high engine oil pressure was set for flight 16 when the first data were obtained. Under some conditions, high engine-oil consumption has been found to be responsible for erratic knock data, particularly in the lean-mixture region.

Another apparent discrepancy in figure 9(a) can be observed between the two curves for the xylidine blend. The data for the curve that shows the higher performance characteristics (flight 21) were obtained approximately 1 month later than the data for the lower curve (flight 15). The fuel for both flights was taken from the same storage batch; the first test was made only a few days after the batch was blended.

In a number of instances it was impossible to obtain knocklimited power data owing to the low capacity of the torquemeter boost pump which, as previously mentioned, was later replaced by a higher-capacity pump. Consequently, in figures 6(a), 7(a), 9(a), and in the subsequent figures that are replots of these data, knocklimited-brake-horsepower and brake-specific-fuel-consumption data are omitted in some cases. Analysis of data. - All the 1800 rpm knock data (figs. 6(a) and 7(a)) are combined for direct comparison in figure 10; similarly, a compilation of the 2230 rpm knock data (figs. 8(a) and 9(a)) is presented in figure 11. In figure 10, the effects of carburetor-air temperature on knock limits for the different fuels at an engine speed of 1800 rpm may be observed; in figure 11 the effects of blower ratio on the knock limits at an engine speed of 2230 rpm can be seen.

The following table presents a brief comparison of the knocklimited performance characteristics of the two fuel blends relative to 28-R. As previously explained, all tests were made with approximately constant cooling conditions; therefore, engine temperature levels were higher with the higher-performance blends.

RATIOS OF KNOCK-LIMITED BRAKE HORSEPOWER OF TEST FUELS

RELATIVE TO 28-R

Conditions->	Engine speed, 1800 rpm; carburetor-air temperature, 86° F; high blower ratio	2230 r	etor-air ature, ; high	Engine speed, 2230 rpm; carburetor-air temperature, 100° F; low blower ratio				
	0.065		ir ratio	0 0/7	0.090			
	0.005	0.005	0.090	0.065	0.090			
80 percent 28-R + 20 percent triptane leaded to 4.5 ml TEI/gal	1.16	1.28	1.19	1.19	1.15			
97 percent 28-R + 3 percent xylidines leaded to 6.0 ml TEI/gal		1.12	1.22	1.30	1.19			

It is observed that the temperature-sensitive xylidine blend showed higher knock-limited performance in the lean range at the milder conditions (low blower) than the triptane blend, but at the more severe conditions (high blower) the xylidine blend fell below the triptane blend.

In general, the increase in performance shown by the triptane blend over that of 28-R for the various conditions investigated compares favorably with the results of small-scale, single-cylinder

knock tests conducted at the Cleveland laboratory. These tests (reported in reference 1) show that, for similar engine conditions, the percentage improvement in knock-limited performance for blends of triptane in 28-R may be predicted for multicylinder engines with reasonable accuracy.

Piston seizure. - A single point is shown near the knocklimited manifold-pressure curve for the xylidine blend in figure 8(a) that is labeled "piston seizure and preignition encountered." At the time check tests (flight 22) were being run with the xylidine blend, the partial failure of piston 2 occurred. The time of this failure coincided with the photographic recording of the test data for this knock point. A rear middle-barrel temperature of approximately 710° F was noted for cylinder 2 whereas the cylinder-head temperature for this cylinder, as recorded by several thermocouples, was essentially normal. At approximately the moment when the data were recorded, preignition was evidenced by a movement of the oscilloscope diagram for this cylinder off the screen to the left. Preignition was accompanied by continuous knock. Within approximately 5 seconds after preignition was first observed on the oscilloscope, the engine operation became rough and a backfire occurred.

Based upon the foregoing observations and data, the following recapitulation is believed to be the sequence of events that occurred. During operation of the engine at this high-power (and high-temperature) condition, where the rear middle-barrel temperature of cylinder 2 was ordinarily somewhat in excess of 400° F, the thermal expansion of piston 2 was sufficient to cause a partial seizure in the barrel, Additional heat was added to the piston due to friction until the piston (or the cylinder wall) became hot encugh to induce preignition. Simultaneously, continuous fuel knock was probably aggravated both by the advanced ignition and by the high piston-head temperature. Surface ignition finally became sufficiently advanced that combustion was taking place while the intake valve was still open and a backfire resulted. It is felt that the high-temperature piston seizure definitely preceded the preignition inasmuch as the cylinder-barrel temperature was extremely high whereas the cylinder-head temperature was approximately normal.

The results of this sequence of events were a badly scuffed and burned piston and a cylinder that was fairly uniformly scored around its entire surface. No other damage to the engine was apparent upon disassembly for inspection. Mixture-temperature data are not shown at the point of piston seizure because the readings taken were unreliable.

Comparison of Knock-Limited Performance, Temperature-Limited
Performance, and Carburetor-Metering Characteristics

Temperature-limited performance characteristics. - In order to compare fuel knock limits with engine cooling limits, four temperature-limited performance curves were calculated and are plotted in figures 12 and 13. The calculations were based on the cooling-correlation method developed in NACA Report No. 612 (reference 7). A cooling correlation was made for the test engine in flight and is presented in reference 6. Knock-limited performance curves for 28-R and the triptane blend, replotted from figures 10 and 11, are included in figures 12 and 13.

The following conditions were selected for presenting the cooling-limited performance relations in figures 12 and 13:

Condition	Maximum rear-spark-plug- gasket temperature ^a (^O F)	Cowl-flap settingb
1	450 (maximum allowable temperature for cruising)	1/3 open (approximately 7° open; maximum permissible cruising setting)
2	450 (maximum allowable temperature for cruising)	"Closed" (approximately $2\frac{1}{2}^{\circ}$ open; recommended cruising setting)
3	400 (desired operating temperature)	1/3 open (approximately 7° open; maximum per- missible cruising setting)
4	400 (desired operating temperature)	"Closed" (approximately $2\frac{10}{2}$ open; recommended cruising setting)

^aValues from manufacturer's operating instructions (reference 8).

bValues from airplane flight manual (reference 9).

The estimated temperature-limited-performance relations in figures 12 and 13 were based on the following assumptions:

- (a) Airplane gross weight of 50,000 pounds
- (b) Flight at 7000-foot density altitude
- (c) Cooling-air stagnation temperature of 60° F
- (d) Carburetor-air temperature of 100° F
- (e) Airplane equipped with four engines, all operating at the same conditions and having the same cooling characteristics as the test engine
- (f) Approximately constant propeller efficiency in the highpower range with change in pitch and change in airspeed
- (g) Variation of true airspeed as a function of the cube root of engine power
- (h) Variation of brake horsepower as a linear function of manifold pressure within the rich range of fuel-air ratio

In the development of the temperature-limited performance curves it was necessary, as fuel-air ratio varied, to correct the cooling-limited engine output for changes in cooling-air pressure drop in accordance with the expected change in airspeed with varying engine power. These performance calculations were facilitated by the use of a cruise control chart for this airplane given in reference 9. These curves therefore represent the dual effects of fuel-air ratio and cooling-limited airspeed on temperature-limited engine output and are, consequently, in part a function of the airplane performance characteristics.

Since the cooling correlation was based on temperature measured at the embedded rear-spark-plug-boss thermocouple, a conversion was made from maximum (of 14 cylinders) rear-spark-plug-gasket temperature (corresponding to the manufacturer's specifications, as shown in the table) to average rear-spark-plug-boss temperature. This conversion was based on temperature data obtained from the flight engine. Comparisons between knock-limited performance and temperature-limited performance are probably more valid on the basis of manifold pressure than on the basis of brake horsepower because values of charge-air flow obtained from the cooling-correlation analysis are more directly related to manifold pressure than to brake horsepower.

Carburetor-metering characteristics. - The third set of curves shown in figures 12 and 13 represents the approximate metering characteristics of the injection carburetor, which is standard for this engine. These carburetor-metering characteristics were obtained from flow-bench test data reported in T.O. No. 03-10BA-3 that were treated in the following manner: A plot of fuel-air ratio against air flow was made; then, with the aid of data obtained in flight showing the relation between manifold pressure and air flow, a plot of fuel-air ratio against manifold pressure was made.

It must be pointed out, in connection with the plotting of these carburetor-metering-characteristic curves, that these relations are based on conventional operation of the carburetor where carburetor inlet-air pressures are approximately atmospheric at ground-level conditions. In the event, however, that an engine-turbosupercharger combination were so operated that the carburetor inlet-air pressure would greatly exceed 30 inches of mercury absolute, these curves would no longer apply because no density compensation is available with standard carburetors for air densities much in excess of ground-level atmospheric conditions. The result of such an operating procedure is to shift such carburetor-metering curves as are shown in figures 12 and 13 in the lean direction. This shift becomes progressively greater with higher carburetor inlet-air densities.

A comparison of the knock-limit curves with the cooling-limit curves in figures 12 and 13 should afford an approximate idea of the feasibility of using a high-performance fuel in this particular airplane-engine combination. It must be pointed out, however, that the knock curves, as mentioned earlier in the report, were run at cooling conditions that tended to penalize the high-performance fuels relative to 28-R. In other words, the airplane actually was not operated so that the test engine could be benefited by a rate of cooling-air flow which would correspond to the actual power being drawn from this engine, as would be the case if the airplane were equipped with four similar engines, all operating at the same conditions.

Comparison of knock limits with cooling limits. - Inspection of the three sets of curves in figures 12 and 13 reveals a number of interesting features. In figure 12, the knock curve for 28-R fuel falls below the highest temperature-limited curve; however, throughout its range it considerably exceeds the curve that satisfies the manufacturer's desired operating conditions (the lowest temperature-limited curve). For the airplane and flight conditions assumed, it appears that engine operation would be possible near the knock limit for the triptane blend, which is 12 or 13 percent higher than that

for 28-R (fig. 7(a)). For operation with the triptane blend, the engine may be cooled within maximum specified temperature limits but apparently not within the manufacturer's desired temperature and cowl-flap-setting limits. It should be pointed out, in connection with the curves for 1800 rpm in figure 12, that these curves are all based on high-blower operation because all the knock data at this engine speed were obtained in this blower ratio. The standard airplane engines have only the low-speed blower; the difference in engine mechanical efficiency between high and low blower was therefore taken into account in the computation of temperature-limited airspeeds, cooling-air pressure drop, and resultant values of temperature-limited engine performance. If these temperature-limited performance curves had been calculated for low blower ratio instead of high blower ratio, all curves would have been shifted upward.

Figure 13 shows that, when the engine is operated at the knock limits of 28-R at 2230 rpm, temperatures corresponding to the manufacturer's desired operating specifications are even further exceeded than at 1800 rpm. It appears questionable to operate at or near knock-limited powers even with 28-R at the higher cruising engine speeds.

Comparison of cooling limits with engine manufacturer's operating instructions and carburetor-metering characteristics, - It is of interest to note the engine manufacturer's operating instructions for various cruising powers at an engine speed of approximately 2230 rpm. Instructions for the double-row radial air-cooled engine specify, for maximum cruise at 2250 rpm, a manifold pressure of 28 inches of mercury absolute for low blower and 29.5 inches of mercury absolute for high blower. (See reference 8.) Both values are quoted for a mixture-control setting of automatic lean. The automatic-lean curve in figure 13 indicates a fuel-air ratio of approximately 0.065 for a manifold pressure of 28 inches of mercury absolute. This point lies nearly on the engine cooling-limit curve for a cowl-flap setting of one-third open and a maximum rear-sparkplug-gasket temperature of 400° F (engine manufacturer's desired value for cruising). By interpolation between the two temperaturelimit curves for closed cowl flaps, this point will be seen also to correspond roughly to a maximum rear-spark-plug-gasket temperature of 420° F with closed flaps.

A comparison of the shape and the position of the carburetormetering-characteristic curves with the knock-limit curves of figures 12 and 13 indicates the changes that might be effected upon the carburetor in order to bring metering characteristics into closer agreement with fuel knock or engine cooling limits. Additional temperature data. - The maximum rear middle-barrel temperatures, corresponding to the cylinder-head temperatures of 400° and 450° F in figures 12 and 13, are plotted in figure 14. The data for these curves were obtained by means of the cooling correlation from which the curves in figures 12 and 13 were derived and apply for both the one-third open and the closed cowl-flap settings. Although these values may appear high, maximum rear middle-barrel temperatures of the order of 400° F are frequently experienced during conventional operation of the double-row radial air-cooled engine in the four-engine airplane. Observation of these temperatures during standard take-off, climb, and landing approach, when the test engine was being operated according to Technical Order operating instructions (reference 10), revealed maximum rear middle-barrel temperatures varying from 390° to 420° F.

Engine condition. - After a total of approximately 70 hours of operation, of which roughly 12 hours were run at or near knocking conditions, the engine was disassembled for overhaul and inspection. This disassembly was necessitated by a high-temperature seizure of piston 2, which has been previously mentioned. All of the pistons and cylinders with the exception of number 2 were found to be in satisfactory condition. The piston rings gave evidence of considerable wear and some were slightly feathered. Bearings throughout the engine were found to be in very good condition.

SUMMARY OF RESULTS

The following results apply for the 14-cylinder double-row radial air-cooled engine installed in a four-engine airplane under the conditions imposed during this investigation:

- 1. Based on brake-horsepower measurements, the blend of 20 percent triptane and 80 percent 28-R had a knock limit from 15 to 28 percent higher than that of 28-R. The improvement was greater at the higher cruising engine speed, 2230 rpm, than at 1800 rpm.
- 2. Based on brake-horsepower measurements, the blend of 3 percent xylidines and 97 percent 28-R, leaded to 6.0 ml TEL per gallon, had a knock limit from 12 to 30 percent higher than that of 28-R at an engine speed of 2230 rpm. The xylidine blend showed higher knock-limited performance than the triptane blend at the milder conditions (low blower ratio) and showed a lower knock limit at the more severe conditions (high blower ratio). This result is in agreement with the greater temperature sensitivity of the xylidine blend.

3. Based on estimated temperature-limited performance relations for this engine, continuous operation at knock-limited power levels, either with 28-R or with the higher-performance blends, will result in engine temperatures exceeding the manufacturer's recommended value for both cylinder heads and barrels. This fact is particularly true for the higher cruising engine speed.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, December 30, 1944.

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TABLE I - FLIGHT CONDITIONS AND FREE-AIR TEMPERATURE

Flight	Fuel	Press altit	tude	Free-air temperature (°F)		Indicated airspeed (mph)	
			Maxi- mum	Mini- mum	Maxi- mum	Mini- mum	Maxi- mum
6	28 - R	7110	7170	54	56	190	197
8	28-R Triptane blend	7160 7110	7160 7160	24 25	24 28	201 201	204 205
10	28-R Triptane blend	7080 7040	7140 7080	50 54	55 55	193 194	197 205
12	28-R Triptane blend	7010 7020	7110 7180	55 55	60 60	194 195	208 206
15	28-R Xylidine blend	7040 7030	7090 7090	61 57	61	190 191	199 203
16	28-R Triptane blend	6930 6970	7040 7040	53 53	55 53	194 194	200 205
20_	Xylidine blend	6850	6900	59	61.	198	205
21	28-R Triptane blend Xylidine blend		6890 6950 6940	52 54 54	56 56 56	191 194 204	200 206 208
22	Xylidine blend	6940	6940	54	54	203	203

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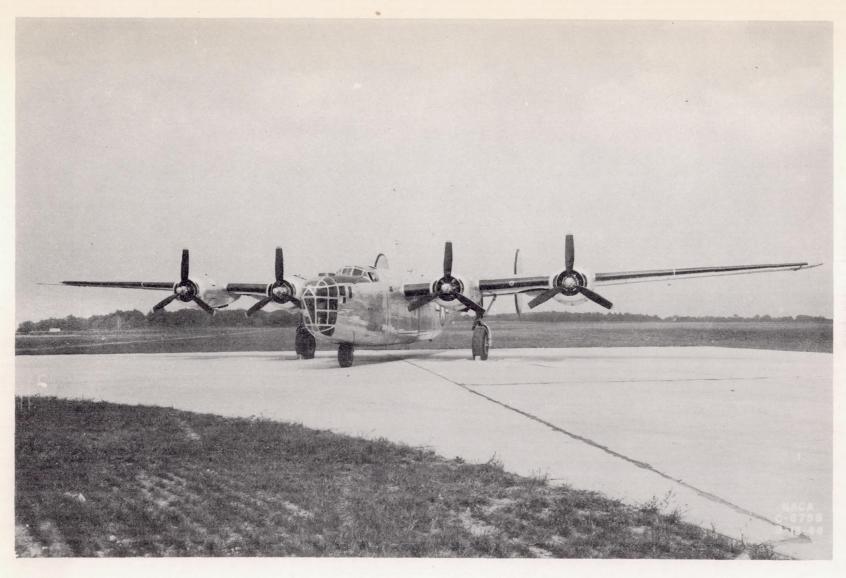
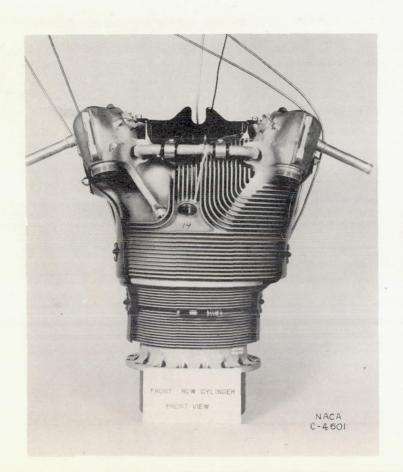


Figure 1. - View of four-engine airplane used for flight knock and cooling investigation.



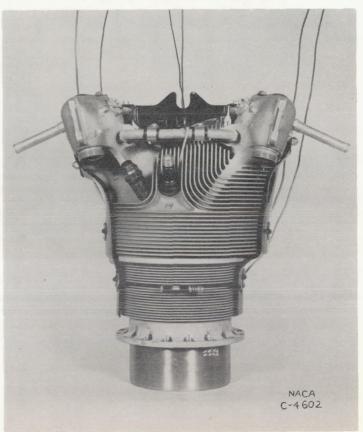
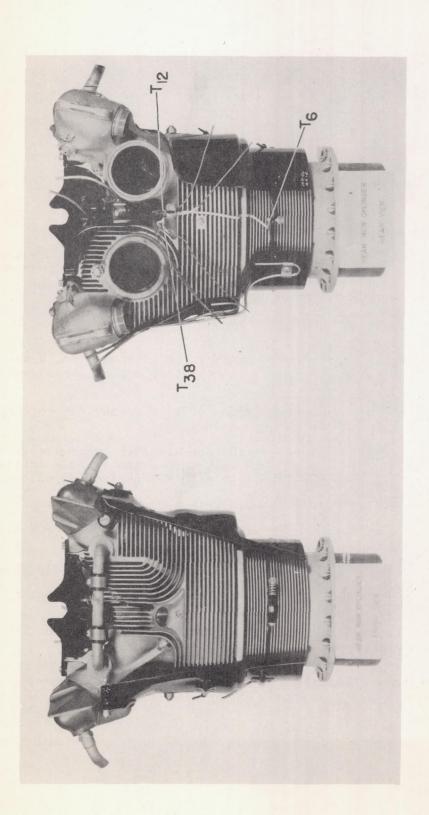
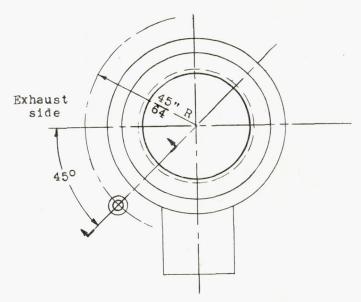


Figure 2. - Typical knock-pickup installation in air-cooled cylinder.

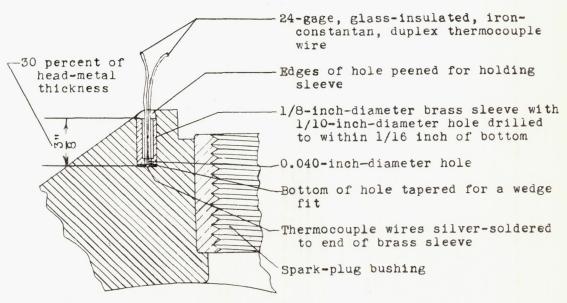


Thermocouple installation on air-cooled cylinders.



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(a) Method of locating thermocouple.



(b) Method of installing thermocouple.

Figure 4. - Methods of locating and installing embedded thermocouple T₃₈ in rear-spark-plug boss on cylinder head of double-row radial air-cooled engine.

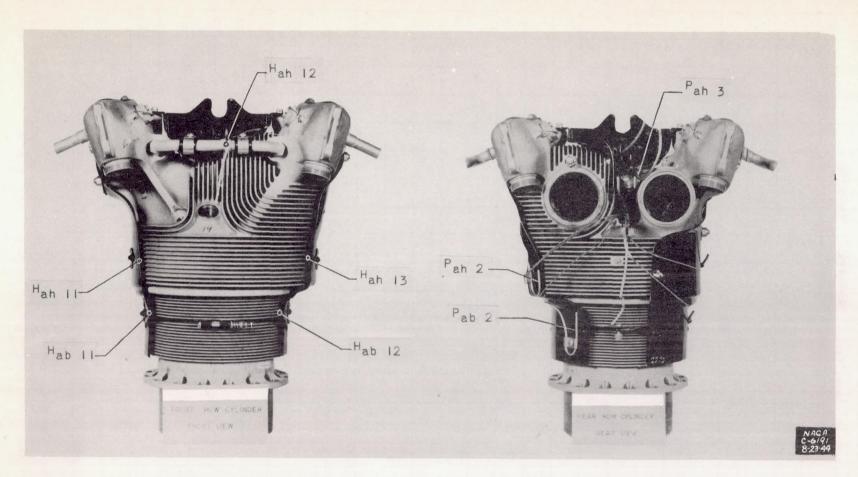
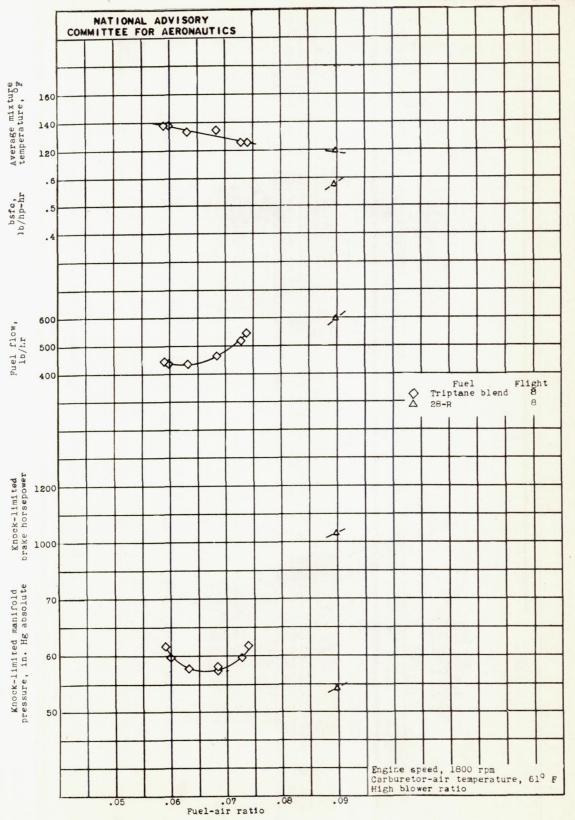
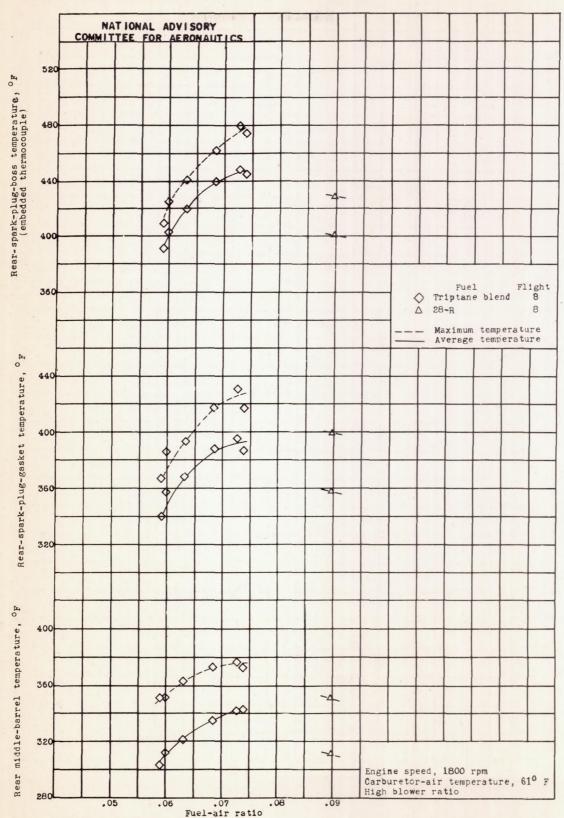


Figure 5. - Pressure-tube installation for air-cooled cylinders.

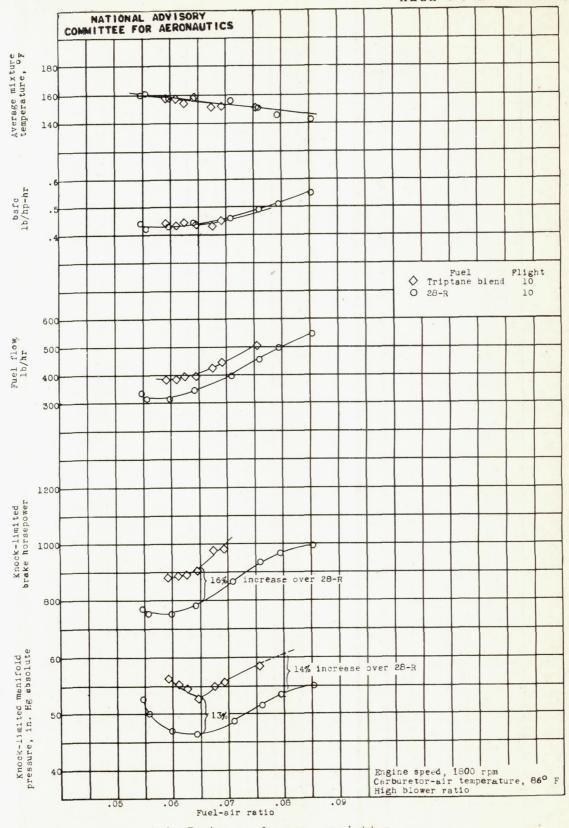


(a) Engine-performance variables.

Figure 6. - Knock-limited performance of double-row radial air-cooled engine installed in four-engine airplane at engine speed of 1800 rpm and carburetor-air temperature of 61° F. Blower ratio, high (8.47:1); spark advance, 25° B.T.C.

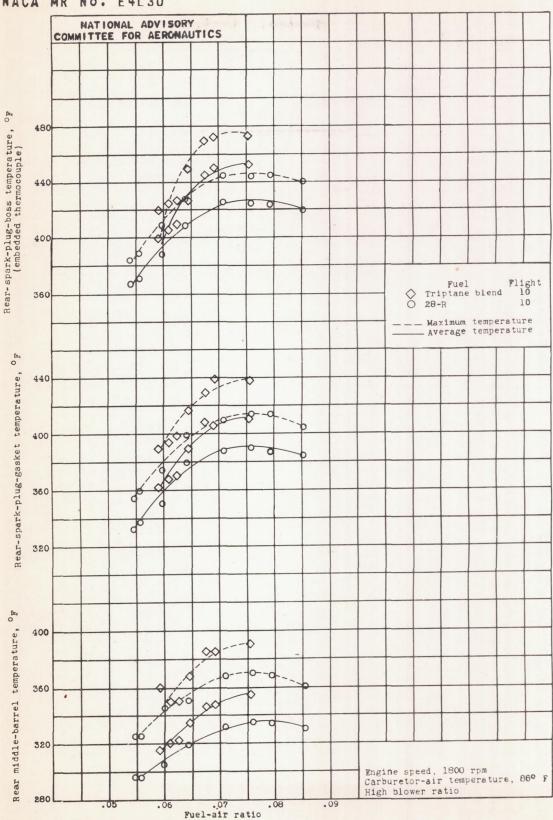


(b) Engine temperatures.
Figure 6. - Concluded.



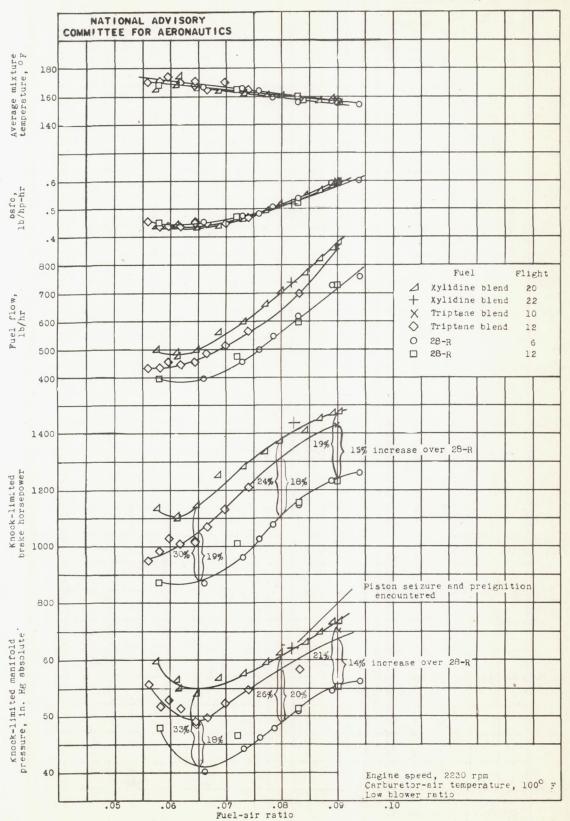
(a) Engine-performance variables.

Figure 7. - Knock-limited performance of double-row radial air-cooled engine installed in four-engine airplane at engine speed of 1800 rpm and carburetor-air temperature of 86° F. Blower ratio, high (8.47:!); spark advance, 25° B.T.C.



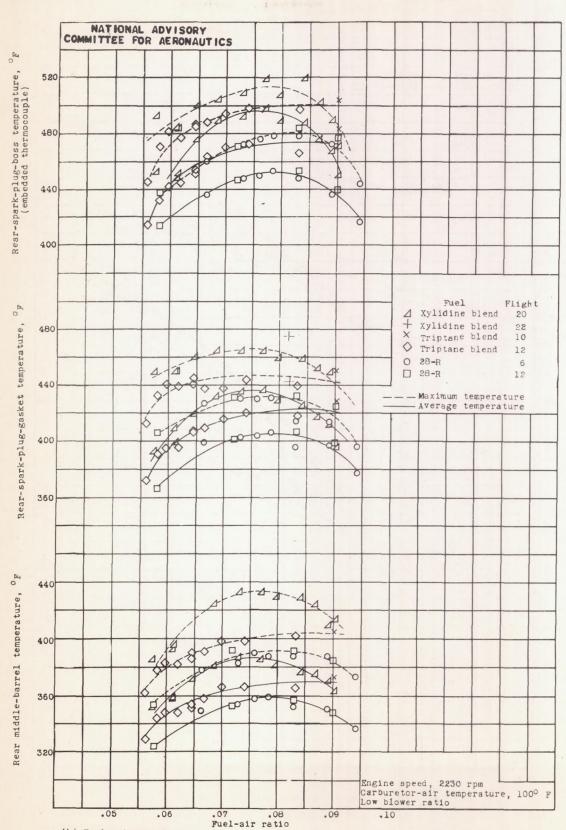
(b) Engine temperatures.

Figure 7. - Concluded.



(a) Engine-performance variables.

Figure 8. - Knock-limited performance of double-row radial air-cooled engine installed in four-engine airplane at engine speed of 2230 rpm and low blower ratio (7.15:1). Carburetor-air temperature, 100° F; spark advance, 25° B.T.C.



(b) Engine temperatures.
Figure 8. - Concluded.

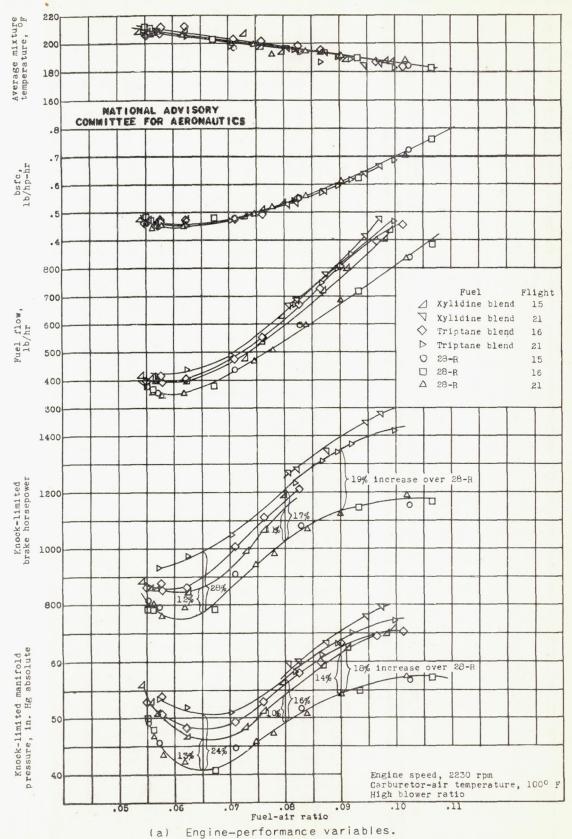
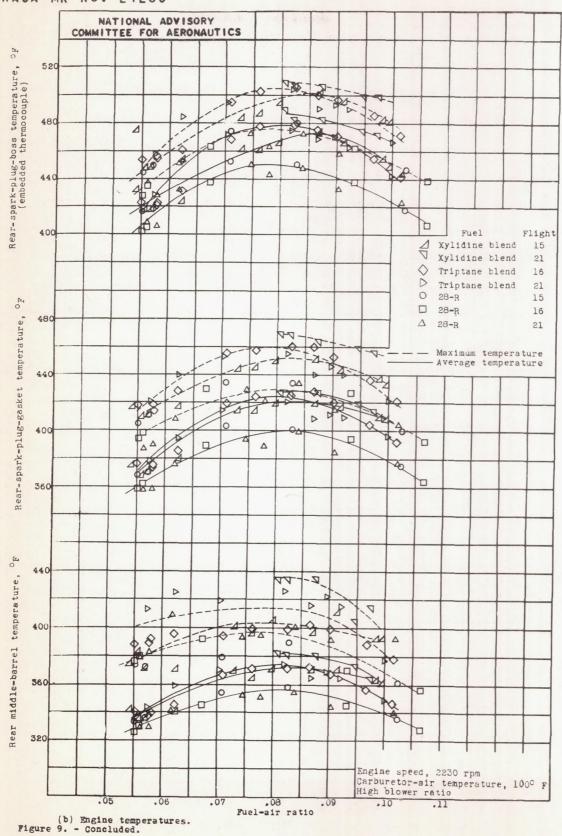


Figure 9. - Knock-limited performance of double-row radial air-cooled engine installed in four-engine airplane at engine speed of 2230 rpm and high blower ratio (8.47:1). Carburetor-air temperature, 100° F; spark advance, 25° B.T.C.



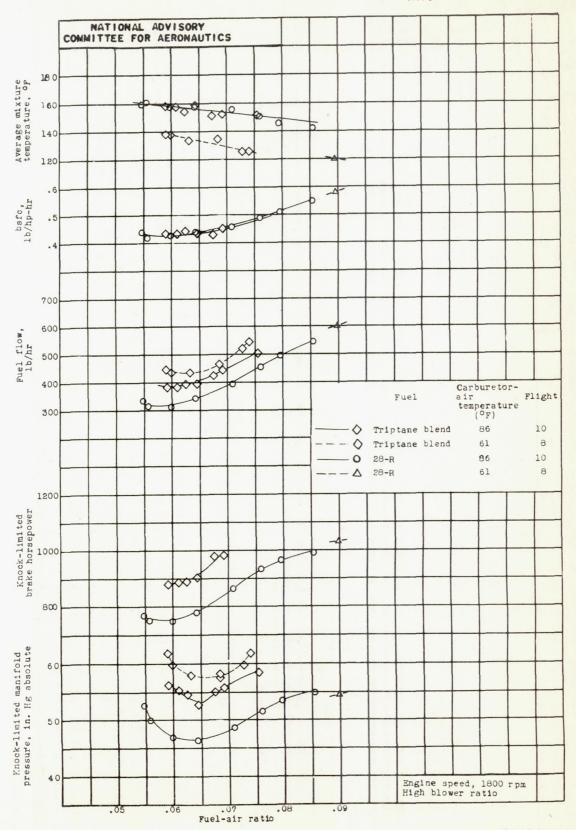


Figure 10. - Comparison of all knock-limited performance data obtained at engine speed of 1800 rpm. Four-engine airplane; double-row radial air-cooled engine; blower ratio, high (8.47:1); spark advance, 25° B.T.C. (Data replotted from figs. 6(a) and 7(a).)

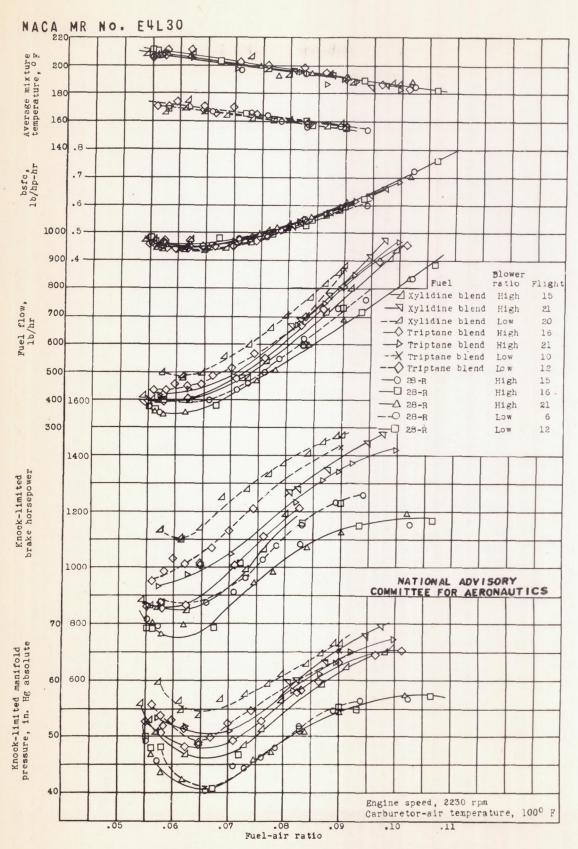


Figure 11. - Comparison of all knock-limited performance data obtained at engine speed of 2230 rpm. Four-engine airplane; double-row radial air-cooled engine; carburetor-air temperature, 100°; spark advance, 25° B.T.C. (Data replotted from figs. 8(a) and 9(a).)

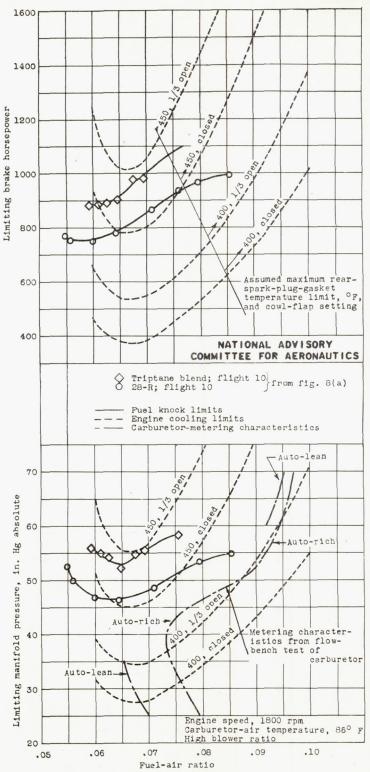


Figure 12. - Comparison of fuel knock limits, engine cooling limits, and carburetor-metering characteristics for double-row radial air-cooled engine installed in four-engine airplane at engine speed of 1800 rpm. (Engine cooling-limit data based on cooling equation for this engine. Airplane assumed equipped with four double-row radial air-cooled engines, all operating at temperature-limited power. Assumed conditions: airplane gross weight, 50,000 lb; cooling-air temperature, 60° F; density altitude, 7000 ft.)

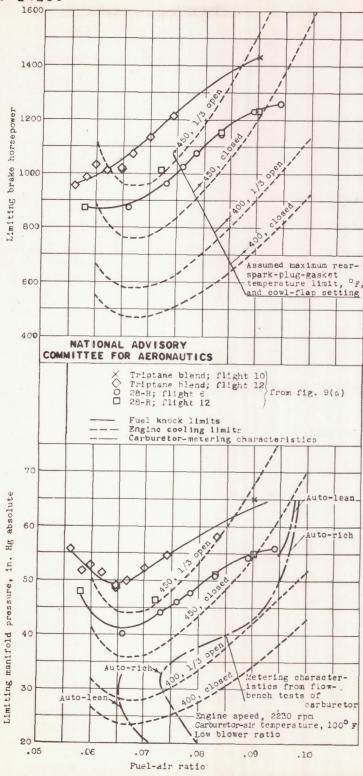


Figure 13. - Comparison of fuel knock limits, engine cooling limits, and carburetor-metering characteristics for double-row radial air-cooled engine installed in four-engine airplane at engine speed of 2230 rpm. (Engine cooling-limit data based on cooling equation for this engine. Airplane assumed equipped with four double-row radial air-cooled engines, all operating at temperature-limited power. Assumed conditions: airplane gross weight, 50,000 lb; cooling-air temperature, 60° F; density altitude, 7000 ft.)

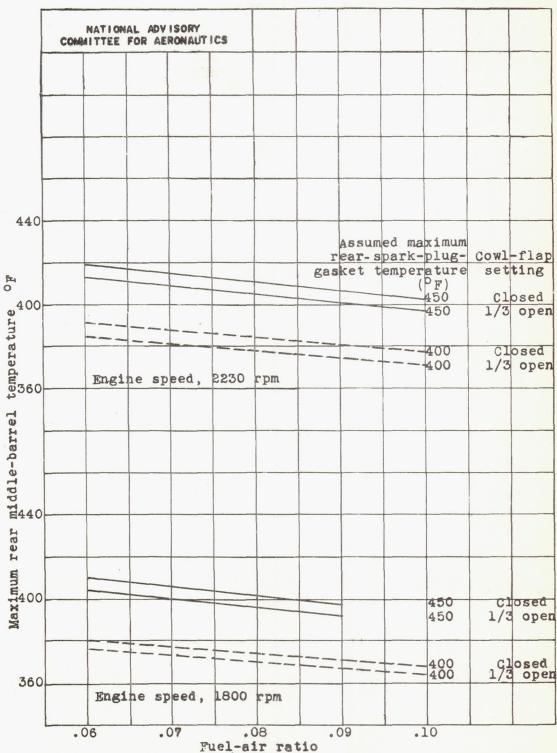


Figure 14. - Variation of maximum rear middle-barrel temperature with fuel-air ratio for two assumed constant maximum rear-spark-plug-gasket temperatures. (Curves correspond to respective temperature-limited performance curves in figs. 12 and 13 for 1/3-open and closed cowl flaps.)